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HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS
VOLUME II
STUDY PARAMETERS INTERRELATIONSHIP

By

R. B. Aronson

February 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
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Two of the key activities in programs to develop higher levels of helicopter equipment reliability are test activities: reliability problem-identification testing and reliability demonstration testing. This document introduces the variables that must be dealt with in testing: demonstrated mean time between failures (MTBF), desired level of confidence, demonstration duration, and probability of passing. It also explains their relationships and the testing strategy which derives from the fact that helicopter hardware must have a real MTBF greater than demonstrated MTBF in order to have a reasonable probability of passing a prescribed demonstration. (Detailed procedures and conclusions are contained in Volume I, Study Results, and Volume III, Sensitivity Analysis.)

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This report, Volume II of a three-volume report, was prepared by the Boeing Company, Vertol Division under the terms of Contract DAAJ02-70-C-0039, Amendment P0001. It presents the results of an effort to further define and discuss selected terminology, assumptions, and variables used in Volume I.

Volume I presented the results of a study to establish the relationships between various reliability demonstration objectives and the test requirements (type, hours, components required, cost, etc.) necessary to achieve those objectives.

Volume II was prepared to give the non-statistician a better understanding of the interrelationships of the many parameters associated with reliability demonstration objectives and their test requirements, as addressed in Volumes I and III.

Volume III further explores the relationship between test costs and quantitative reliability requirements. It also examines the sensitivity of the cost/reliability relationship to those variables whose specific values were selected through engineering judgments in Volume I.

The technical monitor for this contract was Mr. Thomas E. Condon of the Reliability and Maintainability Division of this Directorate.

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VOLUME II: STUDY PARAMETERS INTERRELATIONSHIP

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Abstract

Two of the key activities in programs to develop higher levels of helicopter equipment reliability are test activities: reliability problem-identification testing and reliability demonstration testing. This document (Volume II of a three-volume report) describes the variables that must be dealt with in reliability testing: demonstrated MTBF*, desired level of confidence, demonstration duration, and probability of passing. It also explains their relationships and the testing strategy which derives from the fact that helicopter hardware must have a real MTBF greater than demonstrated MTBF in order to have a reasonable probability of passing a prescribed demonstration. (Detailed procedures and conclusions are contained in Volume I, Study Results, and Volume III, Sensitivity Analysis.)

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*mean time between failures

Foreword

A study to quantify the parameters affecting reliability testing was performed under Contract DAAJ02-70-C-0039 for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia. The results are presented in Volume I, Study Results, and Volume III, Sensitivity Analysis. The work was authorized by DA Task 1F162203A14301.

USAAMRDL technical direction for this study was provided by Thomas L. House and Thomas E. Condon. The author of Volume II was R. B. Aronson of The Boeing Company, Vertol Division, Unit Chief of Product Assurance Methodology and Data Control. He was assisted by K. G. Rummel, T. O. Burke, S. J. Blewitt, and K. H. Eagle of his organization. Program management was provided by G. W. Windolph, Manager of Product Assurance Technical Staff.

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Introduction

We have studied helicopter development testing to find out what kinds of tests are most effective in improving the reliability of the helicopter dynamic system and how much testing is required to meet various reliability levels.

Two kinds of development tests are the key to the achievement of component reliability: problem-identification tests and demonstration tests.

- Problem-Identification Tests are designed to find problems so that they can be fixed.
- Demonstration Tests are conducted after the problem-identification tests have been completed, primarily to evaluate the resultant reliability level and to formulate a statement of what it is.

All of the development tests are described in Volume I. This volume (Volume II) concentrates on the relationships between the problem-identification tests and the demonstration tests. The reader is encouraged to review the detailed procedures and conclusions included in Volume I, Study Results and Volume III, Sensitivity Analysis.

Figure 1 shows how reliability grows by a process of analysis and testing. This process is designed to demonstrate that contractual reliability requirements have been met. Before the development program begins, the user of the equipment and the manufacturer of the equipment numerically analyze the process (going in reverse order from demonstrated MTBF) in order to estimate the magnitude of each element. Our discussion here will also take the steps of the process in reverse order.

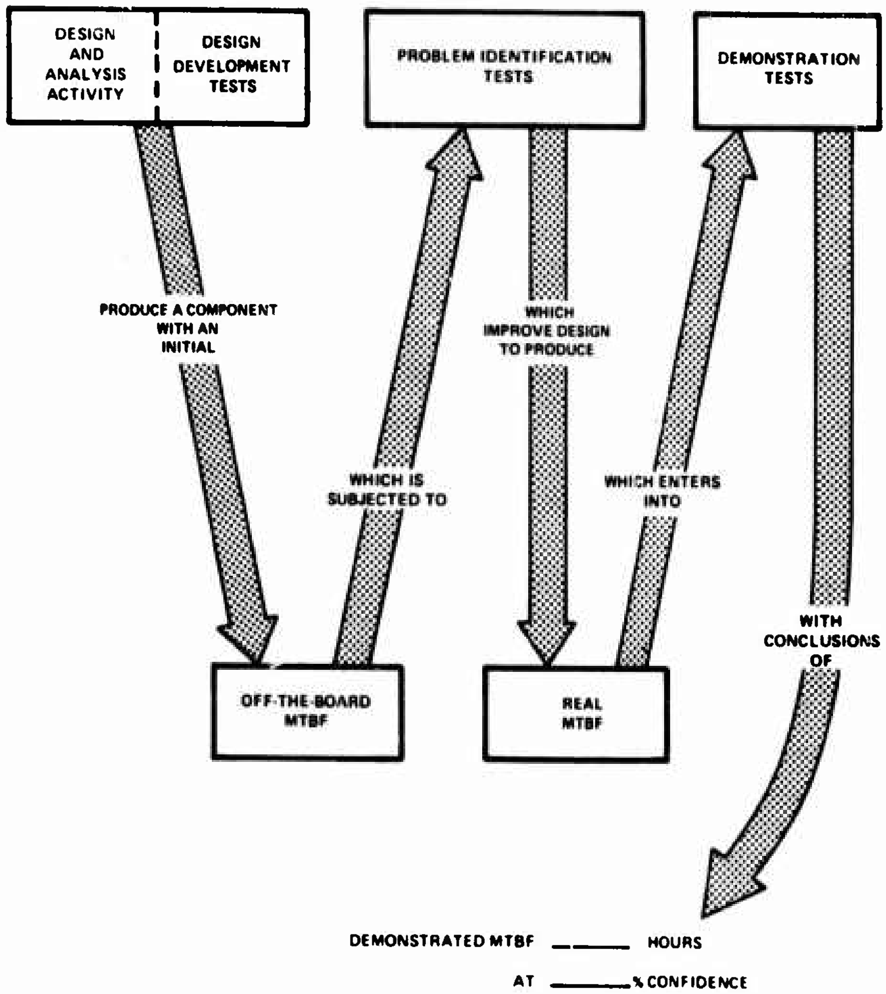

Figure 1. Reliability Analysis and Testing Process.

Reliability Demonstration Testing

A reliability demonstration is a test to show that hardware meets reliability requirements. A small quantity of specimens (called a "sample") is tested for a limited amount of time, and the results are evaluated by the application of probability theory to establish the reliability of the total quantity of parts (called "the population").

Demonstration testing is performed near the end of the development cycle to ascertain that the product meets the reliability requirement. Reliability demonstration testing is performed, not to find problems, but to show that the problems have been eliminated, or that only an acceptable number of problems remain. The testing must be conducted in such a way that:

- There is no doubt about the environment being encountered.
- Hardware configuration is known and kept constant.
- What constitutes failure is unambiguously defined.
- All events are recorded accurately.

There are two types of reliability demonstration: hypothesis testing and interval-estimation testing. The major difference between the two types lies in the evaluation of the test results; the testing of hardware is the same for both.

HYPOTHESIS TESTING

Hypothesis testing is the type of testing described by MIL-STD-781. It uses the number of failures and the operating time to test the hypothesis that: "This is a good lot". Goodness is defined as having a demonstrated MTBF at least as high as the MTBF goal. Levels of decision risk are identified by statistical process. The risk that threatens both the user and manufacturer is that of erroneously accepting bad hardware and rejecting good hardware.

INTERVAL-ESTIMATION TESTING

Interval-estimation uses the number of failures and the operating time to categorize hardware reliability as some specific numerical interval. At the same time, it assigns to the estimate a probability of being correct, called a confidence level.

Interval-estimation testing does not usually provide as early an accept/reject decision as does hypothesis testing. For this reason, higher test costs may be involved where interval-estimation testing is used. This disadvantage is offset by the ability of interval-estimation tests to produce numerical values, which are of value to logistics planners.

Volume I of this report deals exclusively with interval-estimation testing. For this reason, the remainder of Volume II considers interval-estimation testing exclusively.

For example, having observed four specimen failures in 8000 hours operating time, we can state with 90-percent confidence (i.e., nine times out of ten I will be correct) that the demonstrated MTBF of the product is 1000 hours or greater: it lies between 1000 hours and infinity. And that is not the only statement we can make. Statistical techniques produce not one but a family of alternative statements from the same test. Also, at any confidence desired, demonstrated MTBF can be expressed with either a finite or an infinite upper limit:

	Demonstrated MTBF (hours)	
Confidence Level	Finite Lower Limit, Infinite Upper Limit	Finite Upper and Lower Limits
99%	689 or greater	635 to 7422
95%	874 or greater	781 to 4928
90%	1001 or greater	874 to 4061
85%	1101 or greater	942 to 3599
80%	1190 or greater	1001 to 3289
75%	1275 or greater	1053 to 3057
74%	1292 or greater	1062 to 3016
73%	1308 or greater	1072 to 2979
70%	1358 or greater	1101 to 2872
60%	1528 or greater	1190 to 2589
50%	1712 or greater	1275 to 2375
35%	2056 or greater	1400 to 2166

If the same test results can produce a great many alternative demonstrated MTBF intervals, it is also true that any one demonstrated MTBF interval could have been produced by a great many alternative combinations of test results. For example, the resultant 90-percent confidence that the demonstrated MTBF is 1000 hours or more could have been produced by any one of the following sets of test results:

0 failures in 2302 hours
1 failure in 3890 hours
2 failures in 5322 hours
3 failures in 6681 hours
4 failures in 7996 hours ($\sim$ 8000)
5 failures in 9275 hours

HOW MANY FAILURES CAN WE HAVE?

Figure 2 plots confidence level against the amount of time on test (demonstration duration) for a demonstrated MTBF of at least 1000 hours. Consider the first, or zero-failure, line. It says that if we test for 500 hours without a failure, we are 40-percent sure that demonstrated MTBF will be at least 1000 hours. If we test for 2302 hours without a failure, we just reach 90-percent confidence. However, suppose that by the time we reach 2302 hours of testing, we have one failure. The confidence level drops to 67 percent. To reach 90-percent confidence with one failure, we will need 3890 hours of testing.

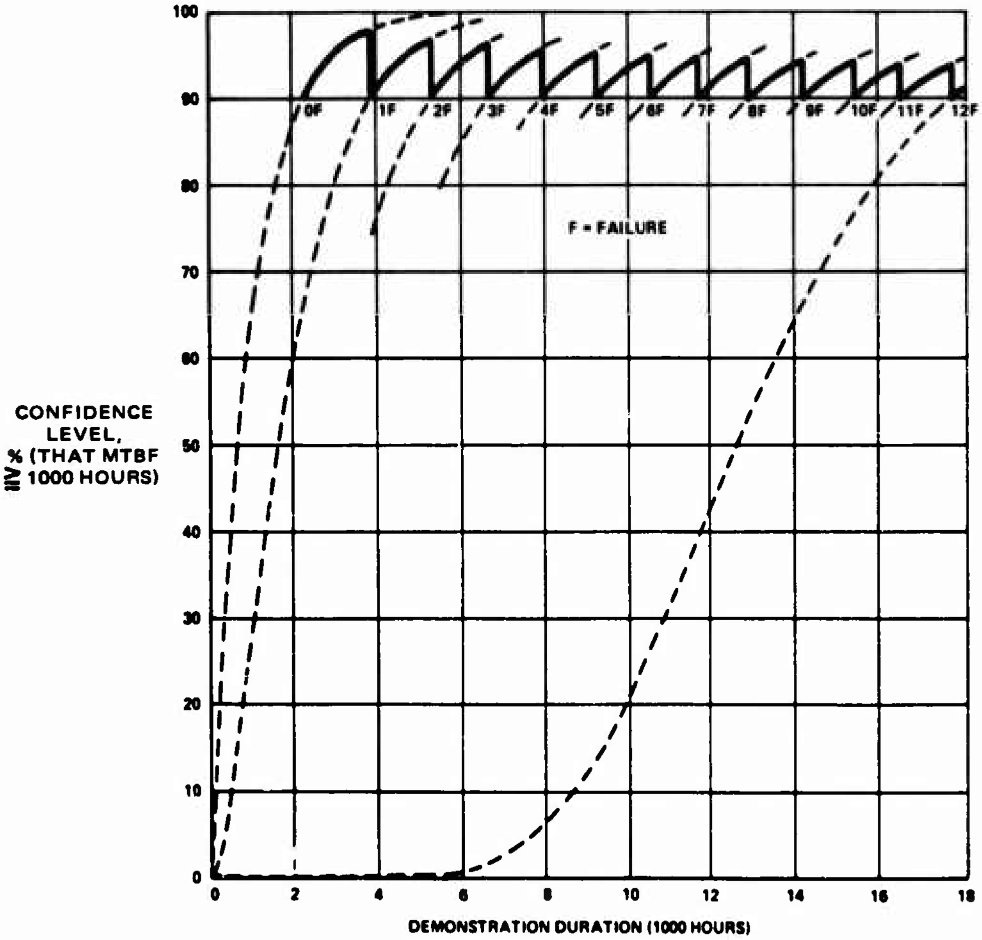

Figure 2. Determining Allowable Number of Failures To Demonstrate an MTBF $\geqq$ 1000 Hours at a Confidence Level $\geqq$ 90%.

Note that if we test for 3890 hours with zero failures, we will have actually demonstrated that MTBF is equal to or greater than 1000 hours at 98-percent confidence level. Thus, regardless of whether we have zero or one failure in 3890 hours of testing, we are fully justified in stating that an MTBF equal to or greater than 1000 hours has been demonstrated at a confidence level of at least 90 percent.

Suppose we choose a test duration of 6000 hours. Three failures will give us a confidence level of 85 percent. For anything more than three failures, the confidence level is still lower. The largest number of failures which allows us a confidence equal to or greater than 90 percent is

two failures: two failures corresponds to 94-percent confidence. One failure gives 98-percent confidence, and zero failures gives 99.75-percent confidence. Thus, two failures or less in 6000 hours of testing guarantees at least 90-percent confidence that the demonstrated MTBF is at least 1000 hours.

It is this changing number of allowable failures that accounts for the step or saw-tooth pattern of Figure 2 and subsequent figures.

A WORD ABOUT TERMINOLOGY

MTBF values developed by testing are commonly called demonstrated MTBFs. Actually, we do not demonstrate MTBF; rather, we demonstrate that the MTBF falls within certain ranges, such as "between 1500 and 10,000 hours" or "greater than 2500 hours", with some numerical level of confidence that this is true. Since it is cumbersome to continually refer to the "range within which the hardware's MTBF has been demonstrated to fall," we use the accepted, convenient, but nondescriptive term "demonstrated MTBF." However, we should remember the meaning behind the term.

Plans for Testing

When a hardware development contract calls for "reliability demonstration at a confidence level of Y-percent that the MTBF of the hardware is equal to or greater than X hours", what do we do? What factors must we consider to ensure that the demonstration requirement will be met?

In order to plan the demonstration tests and problem-identification tests, we must determine what real MTBF is necessary and how it can be achieved. Answering this question involves an examination of the four variables which determine the real MTBF:

- The MTBF to be demonstrated
- The confidence level at which it is to be demonstrated
- The duration of the demonstration test
- The probability of passing the demonstration test

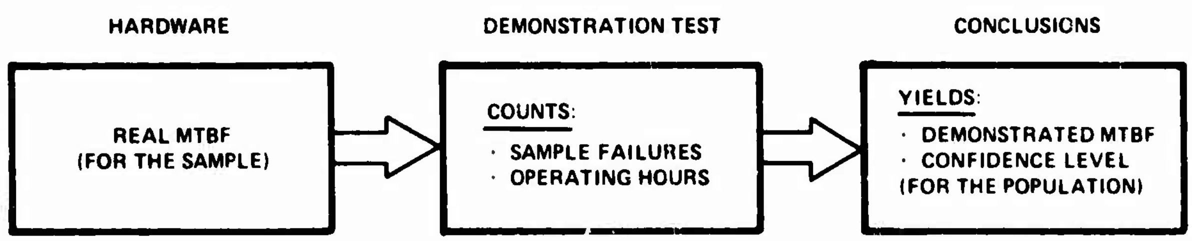

Figure 3. Demonstration Process Relationships.

Figure 3 depicts the relationships in the demonstration process. We will now examine each of the four variables.

THE MTBF TO BE DEMONSTRATED

The value of demonstrated MTBF selected by the user of the equipment establishes the necessary value of real MTBF in accordance with the typical relationship shown in Figure 4. The higher the demonstrated MTBF, the higher the real MTBF entering the test must be.

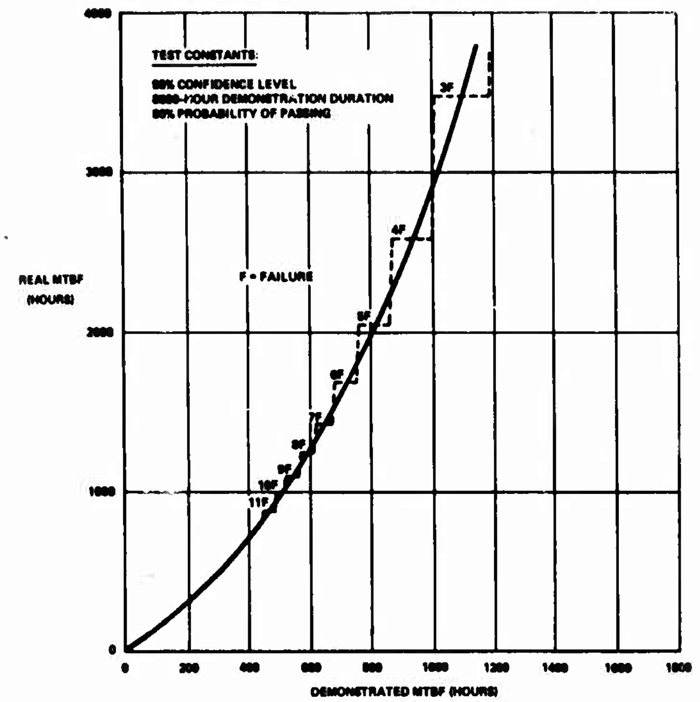

Figure 4.
Real MTBF Must Be Increased To Produce Higher Demonstrated MTBF (When Other Test Variables Remain Constant).

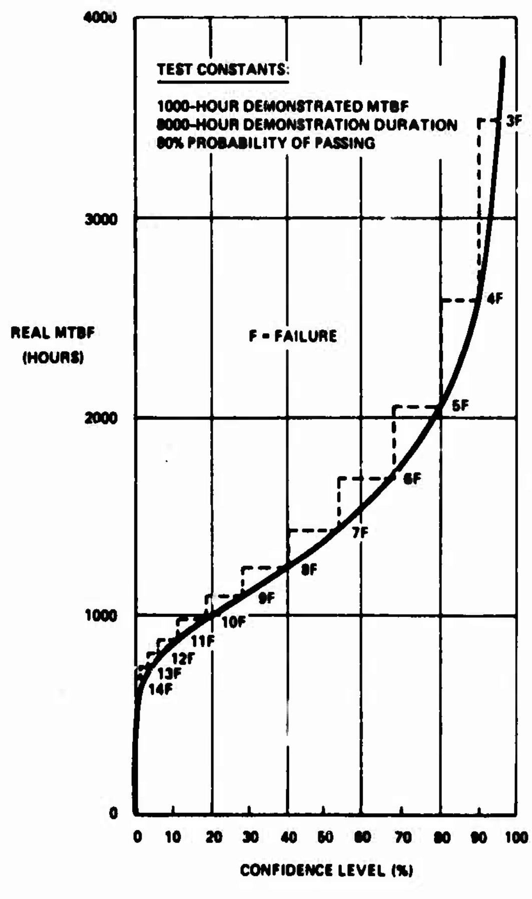

Figure 5.
Value of the Real MTBF Must Be Increased for Greater Confidence Level (When Other Test Variables Remain Constant).

CONFIDENCE LEVEL

How sure are you? 90-percent? 95-percent? Confidence level expresses the probability of our being correct when we make a statement about a hardware characteristic such as MTBF. Certainty is 100 percent. The confidence level that we have in a demonstrated MTBF calculated from test results will always be less than a certainty. The confidence level selected by the user establishes the necessary value of real MTBF in accordance with the relationship shown in Figure 5. The higher the confidence level desired, the higher the real MTBF must be.

DURATION OF THE DEMONSTRATION TEST

Demonstration duration is the sum of all of the test hours on all the hardware specimens in the demonstration. After this number of hours has been accumulated, we count failures and draw conclusions. The demonstration duration agreed upon by the user and the manufacturer establishes the necessary value of real MTBF in accordance with the relationship shown in Figure 6.

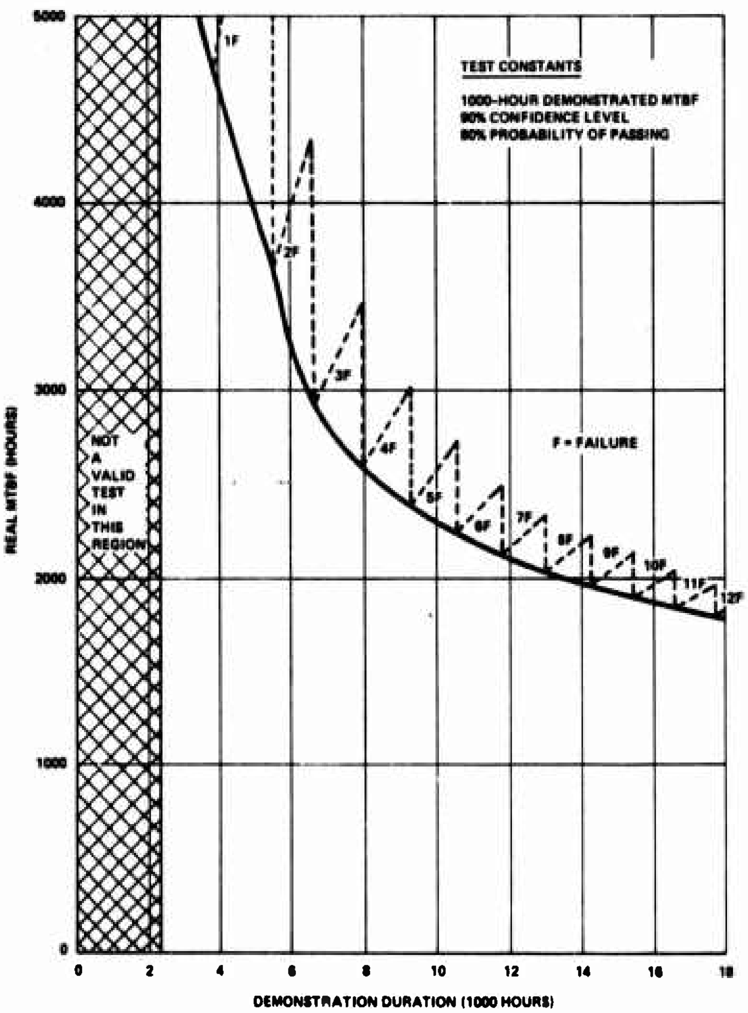

Figure 6. Necessary Value of the Real MTBF Decreases as Demonstration Duration Increases (When Other Test Variables Remain Constant).

This relationship is usually more difficult to understand than the first two; it reflects the way the statistics try to keep luck from affecting the results. Short tests must have fewer failures per hour than longer tests to demonstrate the same MTBF. The longer the test, the lower the real MTBF need be.

PROBABILITY OF PASSING

Regardless of how high the real MTBF may be, there is always less than a certainty (less than 100-percent probability) that the component will pass any given demonstration. For one thing, demonstration tests are not perfect. There is some probability that a test will reject good hardware and pass bad hardware because the behavior of the sample may not be typical of the behavior of the population.

The probability of passing a demonstration test can be calculated. It increases as the real MTBF is increased; it establishes the necessary value of real MTBF in accordance with the relationship shown in Figure 7.

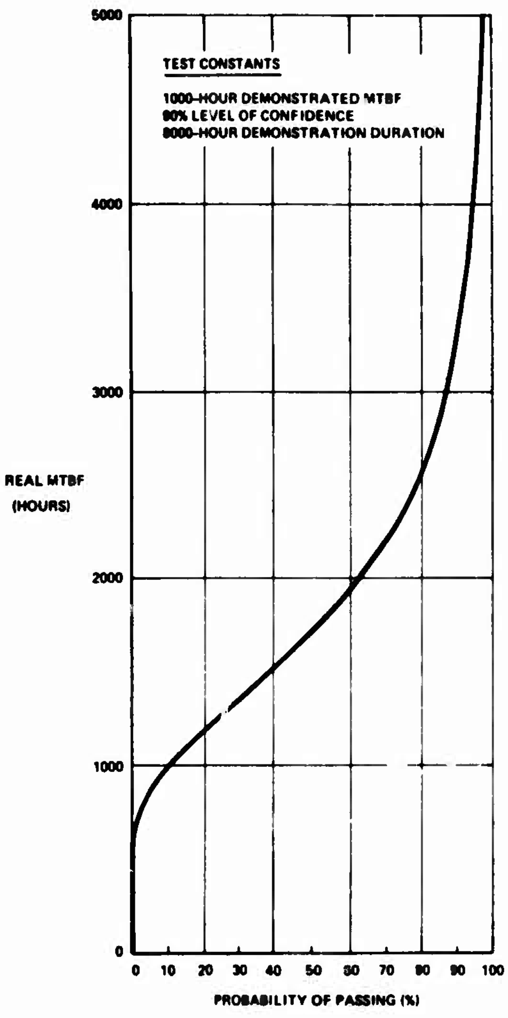

Figure 7. Probability-of-Passing Demonstration Increases With Value of Real MTBF (When Other Test Variables Remain Constant).

Both the user and the manufacturer want high probability-of-passing values: the user because he wants to put his new helicopter into operation on schedule; the manufacturer because he wants to get paid on schedule. The user also realizes that high probability-of-passing values require high real MTBF, which will ultimately reduce his costs of operation and maintenance. However, the higher real MTBFs are achieved only through more development effort, which will require more money. One must compare costs and benefits of the higher MTBFs in order to determine how high the probability of passing should be.

HOW MANY TEST SPECIMENS?

We would like to have enough test specimens to accommodate all reasonable failure-frequency distributions: infant mortality, random failure, and wearout. This implies both short test times on a large number of specimens (infant mortality) and high times on just a few specimens (wearout). These are conflicting requirements.

However, schedule restraints will usually resolve the conflict. On the typical three- to six-year development program, high utilization of test stands is essential. During the initial testing, when infant mortality modes are being encountered, a great number of test specimens is needed. As problems are identified and corrected, MTBF is improved, and specimens run longer between failures. A few components then tend to accumulate a large number of test hours during the final portions of the program and the wearout modes are identified.

For demonstration testing, the number of test specimens is less critical. Most of the problems have been fixed by then, and the few remaining failure modes are likely to be exponentially distributed. The failure rate is constant with hardware age. When this distribution is present, the number of test specimens does not affect test results so long as the specimens are reasonably representative of the range of allowable production variation. Five units, each running for 100 hours, will produce the same number of failures as one unit running 500 hours. Historical data indicate that most major dynamic components have close to an exponential distribution, so that the number of test specimens is not critically important to a demonstration test. The demonstration programs suggested in Volume I employ 15 to 30 different specimens – which is adequate for evaluation purposes.

NECESSARY VERSUS ACHIEVED VALUES OF REAL MTBF

The previous discussions dealt with identification of the necessary value of real MTBF. In so doing, we may have given the impression that we know or can readily measure the achieved value of real MTBF. We can't. To measure the achieved value, we would have to run every component to failure, never repair any failed units, and never build any additional units.

Some say that we should be able to calculate the achieved value of real MTBF from test failure count, operating hours, and a known probability of passing. Unfortunately, demonstration tests do not yield single statements of the achieved value of real MTBF and probability of passing. They involve whole families of statements, as we have seen. Therefore, since one specific probability of passing is never known, the discrete real MTBF present cannot be established. The best we can do is estimate the magnitude of the achieved value through the use of historical data on similar hardware, design analysis, review of test results, and engineering judgment.

Hardware Development

After one has identified the necessary value of real MTBF, the next problem is "How do you get hardware up to that level?"

Two activities contribute to improving hardware reliability during the development phase. The first is the analytical process (which includes certain specialized tests) performed in support of design. This process includes determining sizes, selecting design allowables, making detailed drawings, reviewing the design, and predicting reliability levels. The second involves problem-identification testing of the hardware to detect failure modes. Both of these activities identify deficiencies that would cause unreliability.

It is acknowledged that problem-identification testing overlaps the analytical process. Both activities have the ability to prevent problems from reaching the field, and most development programs employ the two activities in combination. However, we apply testing as a backup process because today's analytical design support process cannot completely eliminate reliability problems. The analytical method holds long-range potential for producing high levels of reliability more cost-effectively, but with the technology available today, we have to rely on testing to meet the reliability goals.

DESIGN AND ANALYSIS

Design and analysis activities are those activities performed during the design phase (prior to the building and testing of hardware) to improve the reliability of the hardware. They include:

- Development of criteria
- Apportionment of goals
- Development of specifications
- Prediction of reliability
- Analysis of failure modes and their effects
- Formal design review

Also included in this activity is a series of specialized tests called design development tests that occur early in the design phase.

DESIGN DEVELOPMENT TESTING

Not all testing directly improves reliability. Volume I used the term design development testing to describe testing that contributed at best indirectly to improved reliability. Design develop-

ment testing includes material testing (sometimes under extreme environments), fatigue testing (to define the shape of the stress-versus-cycles-to-failure curve), and performance testing.

MTBF OFF-THE-BOARD

The MTBF off-the-board is the reliability prediction produced by the design and analysis activities before any problem-identification testing. Reliability is predicted from historical data on similar hardware and analysis of the design to identify suspected failure modes and their frequencies. The prediction process requires some application of engineering judgment.

If the design and analysis activity were completely effective, we would develop an MTBF off-the-board that would equal the real MTBF and hence satisfy the requirements for entering demonstration testing. Since design analysis is not yet that effective, we achieve the necessary value through testing to identify problems, and then take the necessary corrective action.

PROBLEM-IDENTIFICATION TESTING

Problem-identification testing is endurance testing performed to identify reliability problems and subsequently verify the effectiveness of corrective action. It attempts to duplicate the equipment's duty cycle and operating environment for long periods of operation. We use historical relationships between test duration and MTBF improvement in conjunction with the MTBF off-the-board to determine how long the problem-identification test must be in order to achieve the real MTBF.

Figure 8 shows that real MTBF increases as a result of problem-identification testing and corrective action. Determining this relationship for a specific component being subjected to a specific test technique is a complex process. For the design coming off the drawing board, it

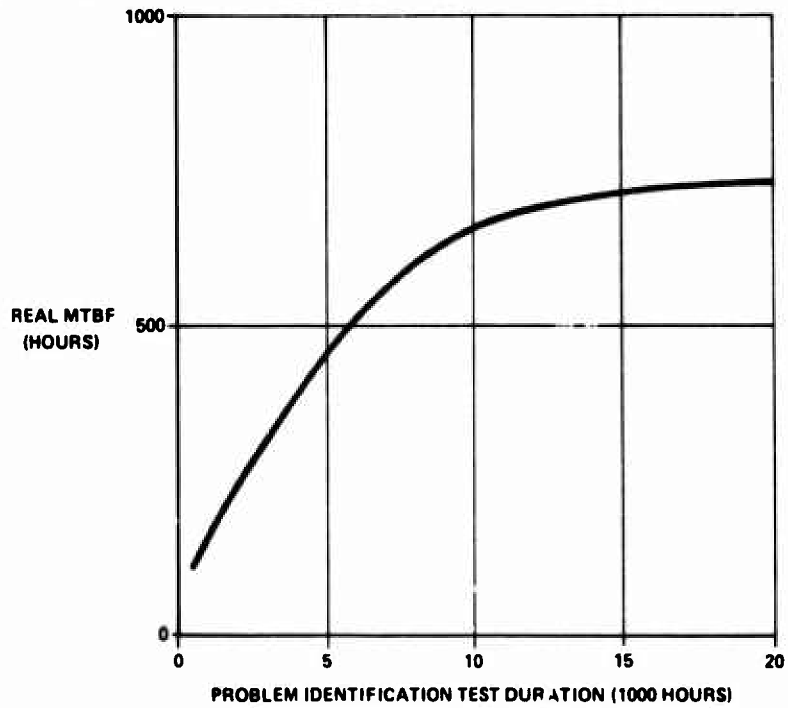

Figure 8. Real MTBF Increases as a Result of Problem Identification Testing and Corrective Action (Example Shown: Single-Rotor Helicopter Main Transmission in "Iron-Bird" Dynamic System Test Rig).

requires analysis of (1) failure modes and frequencies, (2) the effectiveness of specific test techniques in identifying specific problems, and (3) the degree to which each observed problem can be eliminated by a design change. In the basic study (Volume I), discrete values were used to evaluate each of these factors. The effect of choosing different values for these factors is explored in the Sensitivity Analysis in Volume III. Factors explored in Volume III include:

- MTBF off-the-board
- The effectiveness of individual test techniques in detecting problems
- The number of times a problem must be observed in problem-identification testing to postulate that it has been corrected.

Review

This document explains some of the statistical theory used to evaluate reliability demonstration testing. The results of the interval-estimation type of reliability demonstration testing are a range and a confidence level.

In order to have a reasonable probability of passing a prescribed demonstration within reasonable test durations, hardware needs to be developed with a real MTBF greater than the demonstrated MTBF. Determining the necessary value of real MTBF requires consideration of the probability of passing, the demonstration duration, the desired level of confidence, and the demonstrated MTBF.

The process for developing the necessary value of real MTBF involves design and analysis activity and reliability problem-identification testing. A display of these relationships is shown in Figure 9, an expansion of the schematic with which we began this volume.

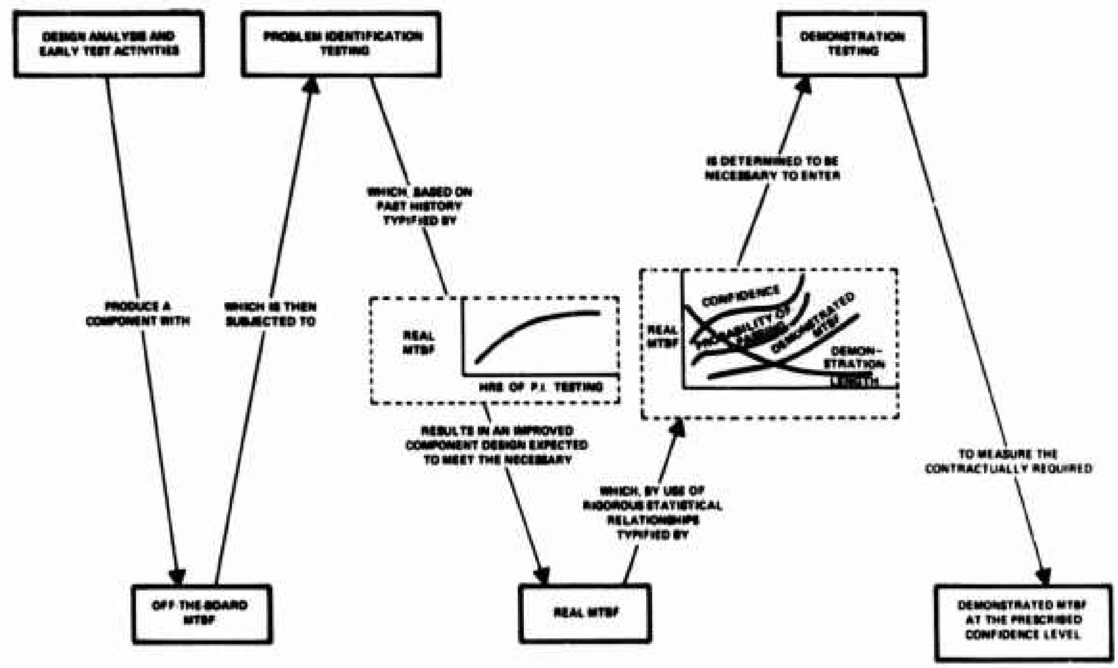

Figure 9. Hardware Reliability Growth Process.

With this background, the reader may wish to review Volume I, Study Results, and Volume III, Sensitivity Analysis. These documents tell how much reliability problem-identification testing is appropriate for various demonstration requirements; they also give typical test-program costs.

Glossary

MTBF

The term Mean Time Between Failures (MTBF) pertains to hardware failure. Failure usually describes a condition where the hardware no longer functions properly, and consequently requires some form of unscheduled maintenance to restore the item (or the aircraft) to the properly functioning condition.

MTBUR

Sometimes the necessary unscheduled maintenance can be accomplished without removing the failed item from the aircraft. For major dynamic components, the failed item is usually removed from the aircraft, repaired, and reinstalled; or the aircraft itself is restored to a properly functioning condition by replacing the failed item with a properly functioning one. The term Mean Time Between Unscheduled Removals (MTBUR) pertains to removals of failed hardware from the aircraft.

MTBR

It has been common practice to remove properly functioning items from the aircraft on a scheduled basis for teardown, inspection, and overhaul, to prevent or reduce the frequency of subsequent failures during flight. The term Mean Time Between Removals (MTBR) considers both the unscheduled removals (due to failure) and the scheduled removals (for preventive maintenance).

TBO

The scheduled removal of items for preventive maintenance (teardown, inspection, and overhaul) occurs at a time referred to as the TBO Interval, where TBO represents Time Between (scheduled) Overhauls.

NOTE: Usage of MTBR and MTBF

Volume I dealt exclusively with major dynamic components installed in helicopters. This relatively expensive, complex hardware nearly always requires removal from the aircraft for repair or replacement in order to restore the aircraft to a properly functioning condition. Further, scheduled removal for preventive maintenance is still practiced, although the goal for future designs is to eliminate or reduce this practice. The term MTBR was, therefore, appropriate to use in Volume I.

In preparing Volume II, it was desired to present maximum applicability to hardware demonstration in general, (i.e., both "items" and "items installed in aircraft" can properly be subjected to reliability demonstration). For this reason, the term MTBF was deemed more appropriate for Volume II.

MTBF OFF-THE-BOARD

The reliability prediction produced by the design and analysis activities before problem-identification testing. (See page 13.)

REAL MTBF

The actual reliability of the component. Particular usage of the term will depend on whether reference is being made to necessary or achieved values. (See page 11.)

DEMONSTRATED MTBF

A range of values developed by testing within which the MTBF falls. The MTBF-to-be-demonstrated is a range selected by the user before demonstration testing begins. (See page 6.)

PROBLEM IDENTIFICATION TESTING

Testing to find problems—so that they can be corrected. (See page 13.)

DEMONSTRATION TESTING

Testing after problem identification and correction to evaluate resultant reliability. (See page 3.)

CONFIDENCE LEVEL

Probability that a specific range of numerical values estimated for demonstrated MTBF will be correct. (See page 9.)

PROBABILITY OF PASSING

Degree of certainty that the component will pass a given demonstration. (See page 10.)

DEMONSTRATION DURATION

The sum of all of the test hours for all of the hardware specimens in the demonstration. (See page 9.)